How we see fossils: developments in palaeontological imaging and visualisation techniques.

Neil D. L. Clark
The Hunterian, University of Glasgow, GLASGOW, G12 8QQ

Introduction

As a student at the University of Glasgow, I remember that there was a book that was heavily thumbed entitled *Handbook of Paleontological Techniques* by Kummel and Raup (1965). It was an epic volume of technical information ranging from the collecting of material, to their preparation and photography. It mentioned the possibility of the use of X-rays and electron microscopy, the use of infra-red and ultra-violet and how to produce a plate of images for publication. All the techniques mentioned are still used today, although with the advent of digital technologies, the possibilities now available have increased substantially. Although this was not the only technical book available for palaeontologists, it was the one that I consulted frequently when using vibro-tools, airbrasive blasters and chemical preparations. I still use the same techniques, but have been attempting to use new, or improved, techniques inspired from watching TV programmes such as *Tomorrow's World* and subsequently *the Gadget Show*. Although this presentation is not going to be a holistic overview of palaeontological techniques, I hope that it will provide an insight into what is possible now and perhaps a little into the future.

Discovering dinosaurs

You might think that it is obvious how people discover dinosaurs. They look for rocks of the right environment and age, and dig a hole. If they are lucky, they find a dinosaur. This is true in most cases, however, in the United States due to some of the fossil bones being radioactive. Ramal Jones discovered a new dinosaur in 1997 solely by using a Geiger counter he had adapted for this purpose. The dinosaur was eventually published on in 1999 and named after him *Animantaryx ramaljonesi* (Carpenter *et al.* 1999). This technique, sadly, cannot be used in all dinosaur hunts as fossils rarely contain radiogenic elements and do not register a detectable radiation level. Notable exceptions include the Miocene mammal bones of Siwalik, Pakistan, and the Devonian fish of Caithness.

Although this perhaps does not come under 'imaging techniques', I think that there may well be a future in producing images of the radioactive hot-spots in an geological exposure as an aid to palaeontological recovery in the same way that ground-penetrating radar and magnetometry are used in other archaeological and geological surveys.

Digital photography

Digital photography has allowed ordinary people to take thousands of photographs of anything and everything. The only restriction now is how much space there is on the memory card. The advantage, of course, is that there is an immediate potential to review and delete without having to wait for the film to be developed and printed. Colour printing of photographs is now available to anyone with a camera (whether on their phone, or as a stand-alone camera) and a colour printer. Resolutions and software are so good that it has been possible to reproduce the fingerprints of a German politician from photographs (Kleinman 2014). This would allow cloning of fingerprints and could become a security issue where fingerprint scanning is used as a security measure, but for this discussion demonstrates the high resolution of even some of the cheaper digital cameras. The disadvantage of digital cameras are the limitations of the image sensor. It may not be sensitive to all the necessary wavelengths of light used in the photography of palaeontological materials, but currently there are also a number of digital cameras that have sensitivity to a range of specific wavelengths such as thermal imaging cameras, gamma sensitive and X-ray cameras. There is even a curved sensor that Sony has developed that will allow focusing on distant object that is not available with the flat sensors – useful perhaps for astronomy, but may find a palaeontological use also sometime in the future especially for microscope photography where edge distortion can be a problem.

Figure 1. Images of *Erettopterus bilobus* from Lesmahagow photographed with (a) incident light; (b) cross-polarised light; (c) red filter; (d) green filter (scale in cm) (GLAHM A2569).

For the amateur palaeontologist most of the high-end photographic equipment is too expensive. However, cheaper digital SLR or compact cameras offer the potential for examining and recording fossils with a resolution that is adequate for publication. Cross-polarised light photography (using polarising filters) can bring out details and contrasts by reducing reflections and recording transmitted light that incident light cannot (Fig. 1). Red – green filters can also help to bring out details when used in conjunction with X-polarised light. Once the images have been taken, software (such as Adobe Photoshop) can be used to blend and subtract images to further enhance the structures that are not always obvious to the observer (Bengtson 2000) (Fig. 2).

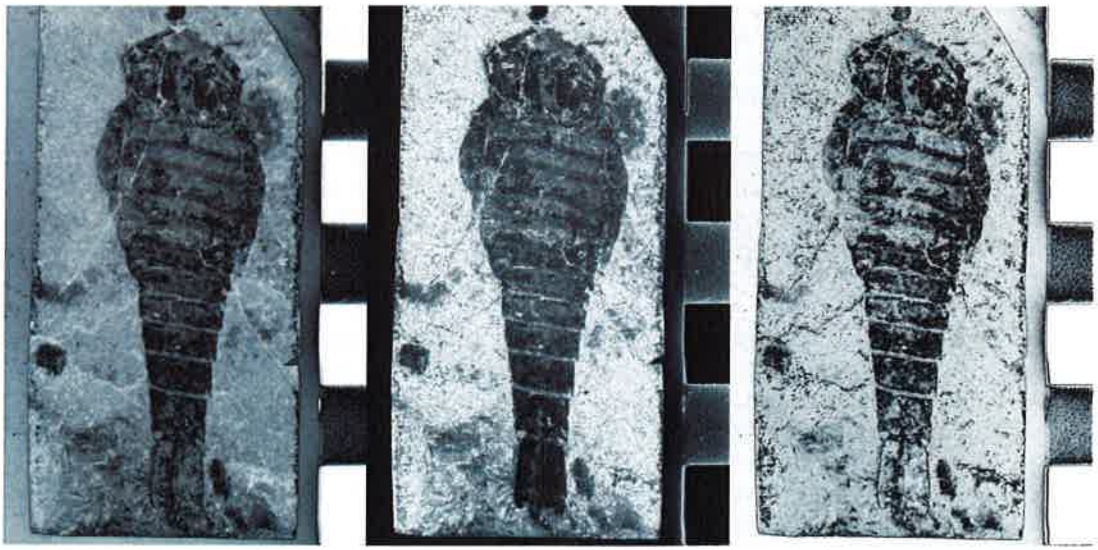

Figure 2. Images of *Erettopterus bilobus* from Lesmahagow: (a) blended difference of red and green filters; (b) cross-polarised light blended difference with green filter and inverted; (c) blended difference of red-green blend and cross-polarised light. (scale in cm) (GLAHM A2569). Structures in the head, for example, may have been overlooked before these techniques were applied.

There are other photographic techniques that can be applied using infrared filters, or ultra violet filters with special sensitive film (Rolfe 1965a, b). Exposure times to allow high resolution images to be taken can be as much as 30 hours (Rolfe 1965a) although with digital cameras it can be as little as 30 seconds. It is possible to do these with digital cameras, but you must be aware of the limitations of the camera. Apparently some cameras have infrared blockers as there can be 'unforeseen' consequences of photographing people in infrared as their clothes may appear invisible (Reuters 1998).

Lasers in palaeontology

Lasers are an easy way to produce accurate 3D images of fossil material (Fig. 3). It is possible to reproduce 3D images from standard photogrammetry more cheaply, but techniques that have been used for landscape analysis and mapping in geographical research have been used to characterise fossils such as dinosaur footprints (Petti *et al.* 2008). The advantage is that the footprint images are free from the subjectivity that is inherent in line-drawings. Comparing 3D images of the footprints can be done using shape analysis software. This is quite an expensive technique and has not yet been applied to insitu dinosaur footprints in Scotland, although it is hoped that this will happen eventually as it will help to inform the site management of conservation procedures as rates of erosion and other damaging processes can be measured.

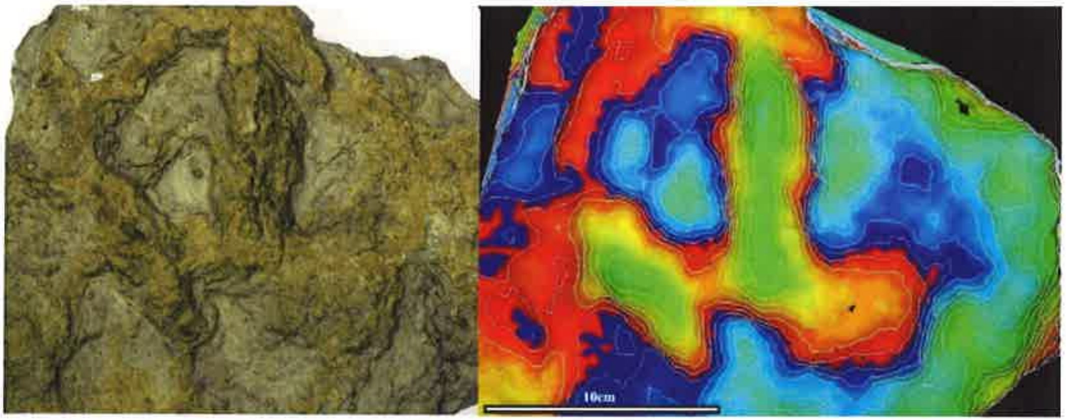

Figure 3. Dinosaur footprint from the Isle of Skye in normal light and image produced by laser scanning showing 1mm height contours using a Leica scanstation c10. (GLAHM 152338).

Another use of lasers is on the microscopic scale. Confocal Scanning Laser Microscopy (CSLM) has been used to look at fossils in amber and more recently in the Rhynie Chert, Aberdeenshire. Normally this technique is used for analysing biological and medical samples by firing different wavelengths of light at the material and recording the fluorescence through various filters. It is most successful in transluscent materials where the fossil fluoresces at a different wavelength than the surrounding matrix. In amber, the fossil plant material fluoresced in the far red, whereas the amber fluoresced in the ultraviolet (Clark & Daly 2010) (Fig. 4). The result was high resolution 3D images of fossil trichomes without damaging the fossil (which would have occurred if traditional serial sectioning had been undertaken).

Figure 4. Trichomes in Mexican amber photographed using (a) a standard microscope and (b) CSLM (field of view = c.1cm) (GLAHM 131494/3) using a BioRad Radiance 2100 fitted to a Nikon Eclipse TE300 inverted microscope.

X-rays and magnetic fields

X-rays have been used to look at fossils for a long time. As early as the 1970s, Professor Wilhelm Stürmer famously photographed pyritised animals in the Devonian Hunsrück slates. A similar method is still used today although most X-ray machines record the information digitally now (Fig. 5).

Figure 5. Pyritised trilobite from a roof slate used in the re-roofing of the Gilbert Scott Building at the University of Glasgow. The slate came from the Ordovician of Spain and was x-rayed courtesy of the Geological Survey, Edinburgh. (a) normal light; (b) x-ray. (GLAHM 152596).

X-rays are also used in CT-scans, but the results are in 3D. This, as well as MRI (which uses magnetic fields to examine the internal structure of fluid-filled soft tissue) were some the techniques used to scan some Chinese dinosaur eggs in 1993 (McJury *et al.* 1994) and subsequently the 'Elgin Marvel' from Clashach Quarry (Clark *et al.* 2004) (Fig. 6). The MRI scanning of the Elgin skull relied on filling the cavity with dense fluid where the fossil once existed. The fluid reacted to the magnetic field produced by the MRI and the resulting data were transformed into high resolution 3D images by manipulation of the segments, seeding and thresholding (Clark *et al.* 2004).

Figure 6. The 'Elgin Marvel' a skull of a dicynodont found at Clashach Quarry and scanned using (a) CT and (b), (c) oblique ventral stereo view using MRI (ELGNM.1995.5.1). (Skull length ~24cm)

At one point the Chinese dinosaur eggs that were scanned in 1993, were taken to a Rolls Royce facility where they were looking into the uses of a new scanner they had developed using neutron activation. Sadly, this did not produce the anticipated results and was abandoned as a technique for looking at fossils. The eggs remained hot with residual radiation for a week or so afterwards.

Micro-CT scanning as well as synchrotron particle accelerators are now often used to scan fossils at immense resolutions. Microscopic structures can be easily resolved and full 3D reconstructions and chemical mapping can be used to provide vast amounts of information on the smallest of fossils (Fig. 7).

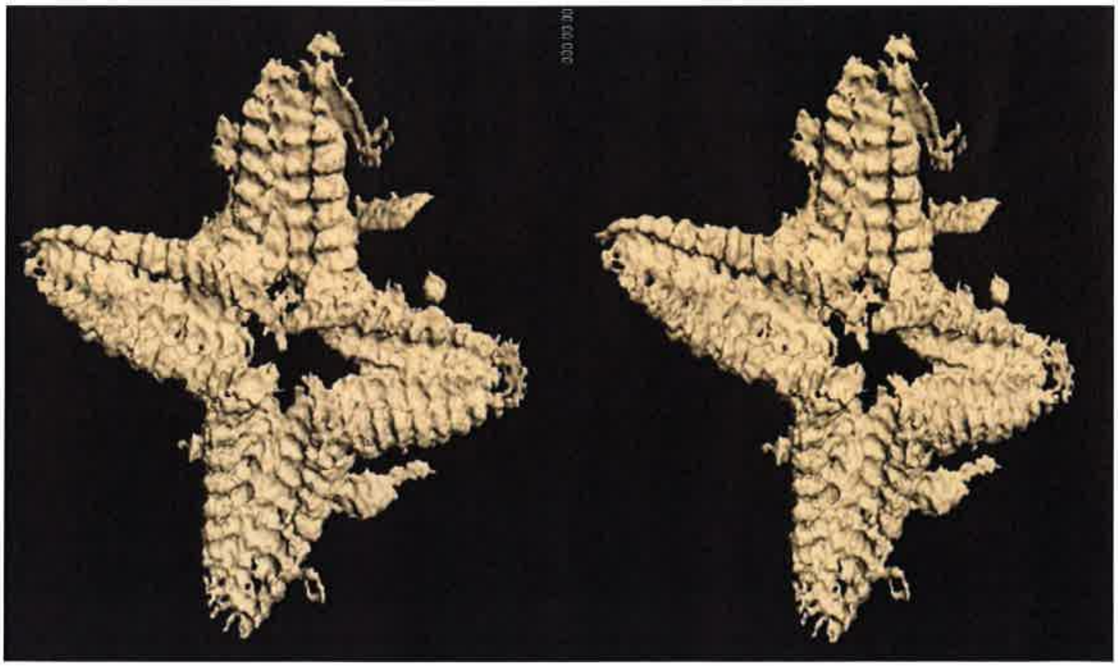

Figure 7. Micro-CT scan stereopair ventral view of a four-armed *Stenaster obtusa* from the Ordovician of Girvan (GLAHM 131619) (width = ~1.4mm)

Elemental Mapping

Scanning electron microscopes (SEM), which use a focussed beam of electrons, have been used to help interpret the taphonomy and morphology of some fossils. This can also produce some very colourful representations of the fossils if a different colour is assigned to the different elements (Fig. 8). The SEM can also be used to produce 3D mapping of a fossil at the micron scale (Fig. 9) – similar to the way lasers can record dinosaur footprints (see Fig. 3).

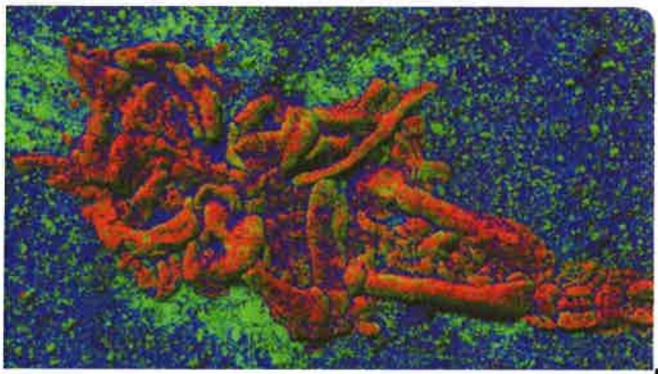

Figure 8. X-ray map generated using the Zeiss EVO 15LS. It shows the unusual preservation of a peculiar type of ancient fish called *Palaeospondylus*. The skeleton of the fish appears as red (phosphorus-rich), cemented by calcium-rich minerals (green) in silicon-rich (blue) surrounding rock. (Copyright Trustees of the Natural History Museum, London).

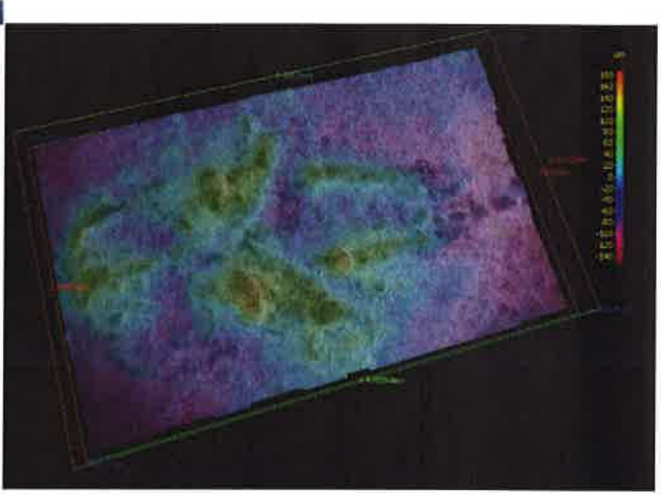

Figure 9. 3D map of the head of *Palaeospondylus* from Achanarras, Caithness using a Carl Zeiss Sigma Field-Emission Analytical SEM.

Moulding and casting

In the past, and still commonly used today, moulding and casting is achieved using rubber latex and silicone (Fig. 10) with resins and plaster (such as jesmonite or plaster of paris). Lamp-black and magnesium oxide is frequently used with latex in order to allow detailed photographs to be taken of internal and external moulds of fossils at the microscopic scale without the problems caused by tonal variations and allow the form of the fossil to be better studied.

Figure 10. A new fossil crustacean from the Carboniferous of the Forest of Dean in (a) natural light and (b) latex peal of the same fossil coated with magnesium oxide.

Although casting is an important part of the process, 3D printing is a method that is gaining in popularity in palaeontology as a direct result of 3D scanning. A tactile representation, sometimes greatly enlarged, of a fossil still held within a rock, is a useful means to a better understanding of the morphology and structure of the fossil. Computer generated imagery where you have control over the scale and rotation of the fossil is extremely useful to a point, but holding an object in your hands helps to better visualise and understand the fossil being researched. It also provides a means of displaying a representation of the fossil in actual, rather than virtual 3D (Fig. 11).

Figure 11. The 'Elgin Marvel' a skull of a dicynodont found at Clashach Quarry as a rapid prototype using a 3D printer from MRI scans of a hole in sandstone. (ELGNM.1995.5.1). (Scale = 5cm)

Statistics and Cladistics

One of the techniques that is being used in taxonomy more and more as a means to quantify the difference between fossils is statistical analysis. New methods of displaying the results and analysing the data are constantly being developed. In the description and taxonomic evaluation, dimensional measurements and shape, both 2D and 3D, are being used more and more in palaeontology. Building data sets of characters for cladistic analysis and a variety of shape measurements help the palaeontologist to differentiate between species.

Here is a new species of Carboniferous crustacean from the Forest of Dean that has been compared with some Scottish crustaceans of a similar age. Landmarks on the carapaces of the three crustaceans are chosen by the author and are defined to be the same for each crustacean. This can then be compared statistically (Fig. 12) using principal coordinate analysis (PCA).

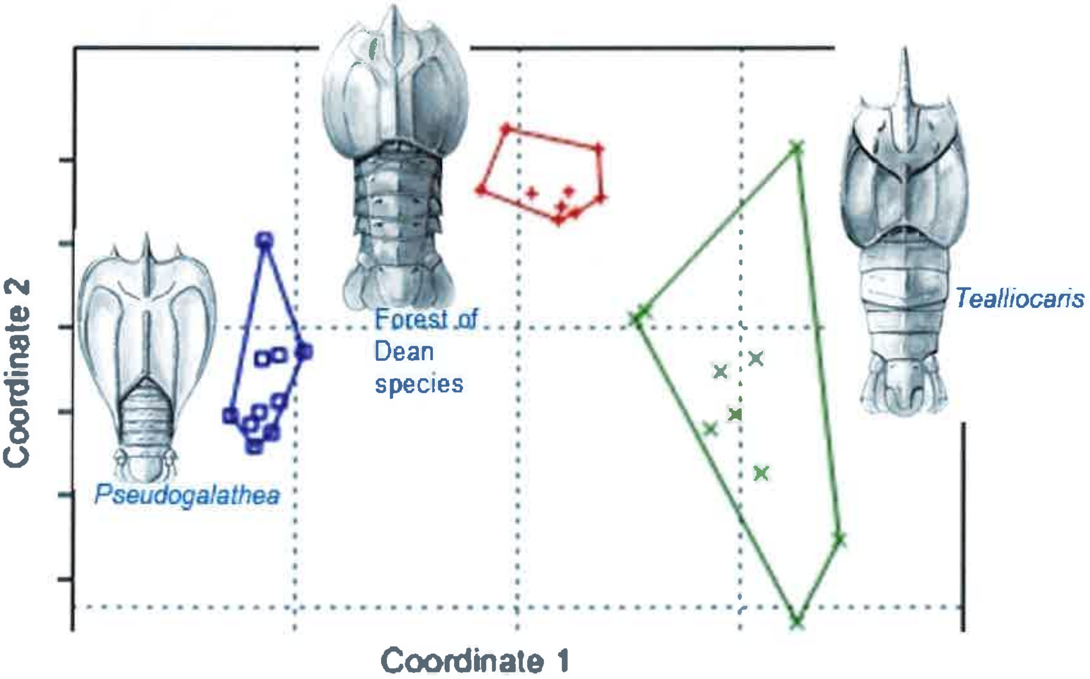

Figure 12. Principal coordinate analysis based on 12 landmarks on the carapace of three Carboniferous crustaceans: *Pseudogalathea*; *Tealliocaris*; and a new crustacean from the Forest of Dean with reconstructions of these crustaceans.

A chosen set of traits that have been used to differentiate between a number of crustacean groups. A related, but substantially different crustacean group is chosen as an 'outgroup'(in this case, the

Leptstraca) to allow a better comparison of relationships within the malacostracan crustaceans to be established and the position of *Tealliocaris* within this (Fig. 13).

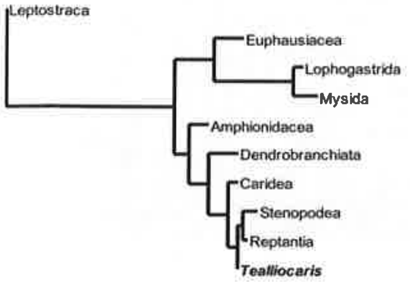

Figure 13. Phyllogram showing the position of *Tealliocaris* amongst the major groupings of the malacostracan crustaceans using the set of characters identified by Richter & Scholtz (2001). This study used a heuristic method optimised following Fitch using PAST software (Hammer *et al.* 2001). The phyllogram suggests strongly that *Tealliocaris* is a decapod crustacean (Dendrobranchiata, Caridea, Stenopodea and Reptantia) rather than a mysid (Lophogastrida or Mysida) or Euphausiacea as has been previously suggested (Clark 2013).

Most descriptive taxonomic works now include a substantial amount of a wide range of data including: lengths; widths; heights; characters; structures; landmarks; and shapes, which all help to build a picture of the fossil being studied and its relationship to other similar fossils. To help analyse these vast data sets, there are software packages that help to manipulate the information into easily understandable graphical formats. The morphological information that palaeontology can provide is sometimes added to the more biological genetic data to provide us with a comprehensive map of life as we now understand it and helps us to understand phylogenies when timelines are added to the fossil datasets. The most common statistical tool now used in palaeontology is principal component analysis (PCA). This allows large datasets to be analysed to show how closely related one morphology appears to be to another. Many software packages are available on the internet including some freeware.

The living fossil

An interesting development is our understanding of the biomechanics of fossil animals. One such a development is in the field of bite strength using von Mises stress which was originally formulated for Materials Science, but which has found an application in fossil animals. It helps us to build up a more complete picture of the living animal and its relationship to its ecology and environment. One example of this is the analysis of the bite of a tyrannosaur where it is was shown that the bite strength was powerful enough to crush a small car (British Broadcasting Corporation 2005).

A useful and popular means of relating the living organism to its environment is the artistic reconstruction of the fossil. Many reconstructions are based on very little evidence, but show the researchers thoughts on how the fossil may have interacted as a living organism. One popular animal frequently reconstructed despite a general paucity of fossil remains are the dinosaurs. The reconstructions of these animals, and our perception of what they were like in life has changed dramatically over the last hundred or more years, from slow lumbering scaly creatures to dynamic colourful feathered animals that have a complex relationship with their environment.

One criticism often levelled at palaeontologists is that they produce fantastically elaborate reconstructions on very little evidence. A fully reconstructed ichthyosaur was produced based on the recently described four and a half bones from the Isle of Skye for example… and it is a new taxon to boot. Although *Dearcmhara shawcrossi* was based on so few bones, there are plenty of closely related more complete animals that provide a template for the reconstruction (Fig. 14). New species in palaeontology are erected on the basis of characteristics unique to those species. In this case, the humerus has all the prerequisite characters that allow it to be assigned to a new species (Brusatte *et al.* 2015).

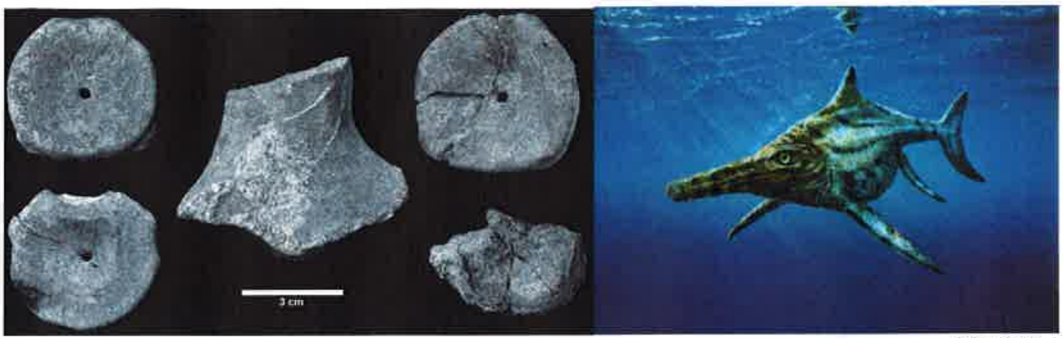

Figure 14. Vertebrae and the humerus of *Dearcmhara* and the reconstruction by palaeoartist Todd Marshall for the PalAlba research group.

Researchers are relying less on the three p's (pens, pencils and paper), and are turning more to the digital graphics tablets format for producing their artwork Producing layers of different tones and opacity helps in the production of high quality easily editable interpretative reconstructions – sometimes even producing 3D models using CAD (computer aided design) software that can be used to produce rapid prototype models.

New developments and the future

It is inevitable that what is said here will be science fiction rather than reality. It could be a wish-list of techniques that would be useful in the future without the technologies being available at the moment. However, it would also be useful if the present-day techniques became cheaper and more widely available. Routine 3D printing and microCT scanning would be immensely useful in palaeontology when trying to visualise objects not normally visible to the naked eye. There will be less of a need to destroy specimens in order to make a mould, a cast, or serial sections.

There are other refinements of methods that are currently being developed to reinterpret structures and their importance. The endocasts of the brain cases of fish and other animals are being studied to demonstrate the evolution and development of the brain. This also helps us to better understand the interactions between the animal and its environment. The sizes of various parts of the endocast of *Tyrannosaurus* suggest that it had an acute sense of smell and was sensitive to low frequency sounds for example (Witmer & Ridgely 2009).

Robotics and the use of computer modelling have been helping us to better understand the biomechanics of fossil organisms. I would imagine that this field of visualisation will increase as modelling software becomes more sophisticated.

Despite all the excitement surrounding the possibility of DNA being recovered from million year old fossils in amber, these claims have more recently been shown to be unreliable (Austin *et al.* 1997). Although a million base pairs of Neanderthals has been sequenced, we are still a great distance from reconstructing and cloning either the cave bear, woolly mammoth or Neanderthals. (Mardis 2008). With the advent of polymerase chain reaction processes, it has become a lot easier to sequence DNA, even the highly degraded sub-fossil material. Perhaps one day we will be able to produce the ultimate in fossil visualisation - a living organism to study rather than just their decayed remains. Then we will have to face the ethical dilemma of whether it is right to bring extinct organisms back to life into an environment to which they may not be well adapted.

References

Austin, J. J., Ross, A. J., Smith, A B., Fortey, R. A. & Thomas, R. H. 1997. Problems of reproducibility – does geologically ancient DNA survive in amber–preserved insects? *Proceedings of the Royal Society of London: B.* **264,** 467-474.

Bengtson, S. 2000. Teasing Fossils out of Shales with Cameras and Computers. Palaeontologia Electronica, vol. 3, issue 1, art. 4: 14 pp., 7.7 MB http://www-odp.tamu.edu/paleo/2000_1/fossils/issue1_00.htm

British Broadcasting Corporation 2005. The Truth About Killer Dinosaurs: episode 1. http://www.bbc.co.uk/sn/prehistoric_life/tv_radio/killer_dinosaurs/programmes1.shtml (viewed 24 February 2015).

Brusatte, S. L., Young, M. T., Challands, T. J., Clark, N. D. L., Fischer, V., Fraser, N. C., Liston, J. J., MacFadyen, C. C. J., Ross, D. A., Walsh, S. & Wilkinson, M. 2015. Ichthyosaurs from the Jurassic of Skye, Scotland. *Scottish Journal of Geology.* **51,** http://sjg.lyellcollection.org/content/early/2015/01/07/sjg2014-018.full.pdf+html

Carpenter, K., Kirkland, J.I., Burge, D.L., & Bird, J. 1999. Ankylosaurs (Dinosauria: Ornithischia) of the Cedar Mountain Formation, Utah, and their stratigraphic distribution. *In:* Gillette, D. (Ed.) *Vertebrate Paleontology in Utah. Utah Geological Survey Miscellaneous Publication 99-1.* 243-251.

Clark, N.D.L. 2013. *Tealliocaris:* a decapod crustacean from the Carboniferous of Scotland. *Palaeodiversity.* **6,** 107-133.

Clark, N. D. L. & Daly, C., 2010. Using confocal laser scanning microscopy to image trichome inclusions in amber. *Journal of Paleontological Techniques.* **8**, 1-7.

Clark, N. D. L., Adams, C., Lawton, T., Cruickshank, A. R. I. & Woods, K. 2004. The Elgin marvel: using magnetic resonance imaging to look at a moldic fossil from the Permian of Elgin, Scotland, UK. *Magnetic Resonance Imaging.* **22,** 269-273.

Cruickshank, A. R. I., Clark, N. D. L. & Adams, C. 2005. A new specimen of *Dicynodon traquairi* (Newton) (Synapsida: Anomodontia) from the Late Permian (Tartarian) of northern Scotland. *Palaeontologica Africana.* **41,** 35–43.

Hammer, Ø., Harper, D.A.T. & Ryan, P. D. 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica.* 4, 9pp.

Kleinman, Z. 2014. Politician's fingerprint 'cloned from photos' by hacker. http://www.bbc.co.uk/news/technology-30623611 (website sourced 23.01.2014).

Kummel, B. & Raup, D. 1965. *Handbook of Paleontological Techniques.* WH Freemand & Co., San Francisco and London. 852pp.

Mardis, E. R. 2008. Next-Generation DNA Sequencing Methods. *Annual Review of Genomics and Human Genetics.* **9,** 387–402.

McJury, M., Clark, N. D. L., Liston, J. J. & Condon, B. 1994. Dinosaur eggs structure investigated by MRI. *Proceedings of the Society of Magnetic Resonance.* **2nd meeting,** p706.

Petti, F. M., Avanzini, M., Belvedere, M., De Gasperi, M., Ferretti, P., Girardi, S., Remondino, F. & Tomasoni, R. 2008, Digital 3D modelling of dinosaur footprints by photogrammetry and laser scanning techniques: integrated approach at the Coste dell'Anglone tracksite (Lower Jurassic, Southern Alps, Northern Italy). *Studi Trent. Sci. Nat., Acta Geol.*, **83,** 303-315.

Reuters 1998. http://www.deadmedia.org/notes/38/380.html

Rolfe, W. D. I. 1965a. Uses of infrared rays. *In* Kummel, B. & Raup, D. (eds). *Handbook of Paleontological Techniques.* WH Freemand & Co., San Francisco and London. 345-350.

Rolfe, W. D. I. 1965b. Uses of ultraviolet rays. *In* Kummel, B. & Raup, D. (eds). *Handbook of Paleontological Techniques.* WH Freemand & Co., San Francisco and London. 350-360.

Stürmer, W. 1970. Versteinerungen mit Röntgen-Augen gesehen. Die Röntgenaufnahme als Hilfsmittel der Paläontologie. *Neue Erlangen.* **22,** 1640-1647.

Witmer, L. M. & Ridgely, R. C. 2009. New insights into the brain, braincase, and ear region of tyrannosaurs (Dinosauria, Theropoda), with implications for sensory organization and behavior. *Anatomical Record.* **292,** 1266-1296.